DEVELOPMENT OF RUGGED ENVIRONMENTAL MONITORING UNITS FOR HUMIDITY AND TEMPERATURE

R. A. Eigenberg, J. A. Nienaber, T. M. Brown–Brandl, G. L. Hahn

ABSTRACT. *Research on the effects of thermal environments requires monitoring and control based on temperature and humidity measurements. There are many approaches to both temperature and humidity measurements, but few offer high reliability in hostile environments with acceptable accuracy and relatively low cost. The Biological Engineering Research Unit at the U.S. Meat Animal Research Center (USMARC) evaluated two separate units that were developed with commercially available sensors for meeting the cost/performance criteria: 1) a linear temperature sensor designed around a National Semiconductor LM35CA, and 2) an Ohmic Instruments Company ABS 300 sensor. This article details sensor calibration and performance.*

Keywords. *Thermal environment, Monitor, Temperature, Humidity.*

Many of the problems in agriculture involve relationships among temperature, humidity, and moisture. For animal production agriculture the interplay between temperature and humidity can be critical, as there is a defined range of thermal conditions within which animals can maintain homeothermy through behavioral and physiological means, while continuing to consume feed at levels needed to maintain production and health (Hahn, 1994). Management decisions for livestock or environmental control systems require accurate temperature and humidity measurements. Livestock research also requires accurate monitoring and control of environment to develop needed relationships and models of animal performance.

Electronic sensors may be vulnerable to typical confined animal environments containing numerous gases including NH_3 and H_2S (Wood et al., 2001). In addition to the potentially corrosive gases, confinement facilities often experience high moisture levels and high particulate levels. The combination of dust, gases, and humidity can degrade sensor performance. Achutan et al. (2001) compared instrumentation response in a swine confinement building over a period of one year. Humidity (HMW60U, Vaisala, Helsinki, Finland) and temperature (Smart Reader Plus 7, ACR Systems Inc., Surrey, British Columbia) measurements were compared to measurements taken using a sling psychrometer. Achutan et al. (2001) found that the one year's collection of humidity measurements made with the HMW60U regressed linearly against the psychrometer measurements had a 95% confidence level centered about 65% RH of ±4.6% which expanded to ±11% near the extreme values of 40 and 100% RH. The linear regression R^2 value for the HMW60U measurements versus the psychrometer readings was 0.53. The temperature measurements were more consistent over the year; the Smart Reader Plus 7 compared to the dry bulb mercury thermometer had a R^2 of 0.73 (Achutan et al., 2001). Achutan et al. (2001) concluded that the instrument's accuracies diminished over time and if instruments of this type are to be used in working confinements, they should be serviced at least on a monthly basis.

The objective of this article is to evaluate a temperature/ humidity measurement system based on sensors offering potentially rugged, reliable, and stable measurements.

MATERIALS AND METHODS

HUMIDITY SENSOR

Humidity was measured using an absolute humidity sensor made by Ohmic Instruments Co. (Easton, Md.), a manufacturer of biomedical and environmental sensors, instruments, and controls. The ABS–300 sensor (fig.1a and 1c) consists of two matched thermistor elements; one is hermetically glass–encapsulated in dry nitrogen, the other is exposed to the environment. When the thermistors are energized, the heat dissipated from the sealed thermistor is greater than the exposed thermistor, due to the higher thermal conductivity of dry air. The difference in resistance between the thermistors is directly proportional to absolute humidity. Absolute humidity, AH, is the mass concentration or density of water vapor given by the mass of water vapor (M_w) per unit volume of gas (V), (g/m^3) (Quinn, 1985).

$$AH = M_w / V \qquad (1)$$

The authors are **Roger A. Eigenberg, ASAE Member**, Agricultural Engineer, **John A. Nienaber, ASAE Member Engineer,** Agricultural Engineer, **Tami M. Brown–Brandl, ASAE Member Engineer**, Agricultural Engineer, and **G. Leroy Hahn, ASAE Fellow Engineer**, Agricultural Engineer, USDA–ARS U.S. Meat Animal Research Center, Clay Center, Nebraska. **Corresponding author**: Roger A. Eigenberg, P.O. Box 166, Clay Center, NE 68933; phone: 402–762–4272; fax: 402–762–4273; e–mail: eigenberg@email.marc.usda.gov.

The manufacturer of the ABS–300 sensor states: "These sensors are very durable. They operate at high temperature and are resistant to chemical vapors due to the use of inert materials–of construction . . .", additionally, the sensors are not affected by condensation and offer negligible long term drift (Ohmic Instruments, 1998). The ABS–300 is immune to the effects of dust based on personal communication with technical support at Ohmic Instruments. This sensor was chosen on the basis of the manufacturer's stated durability and reliability. A simple resistor network provides a 0– to 13–mV output equal to the range of 0 to 130 g/m^3; the manufacturer supplies a table of absolute humidities and corresponding mV outputs for the non–linear response. However, the sensor is nearly linear ($R^2 > 0.99$) over a reduced operating range of 0 through 40°C and AH between 5 and 20 g/m^3, based on manufacturer's literature. The ABS–300 sensor is calibrated using a one–point calibration potentiometer (Ohmic Instruments Co., Easton, Md.), thus setting the operating point to match the published calibration curves.

HUMIDITY MEASUREMENT SYSTEM

The research needs at MARC require that AH be displayed and a high level output signal be available from the humidity sensing system for data logging. The sensor output was amplified by a Burr–Brown 1NA114 instrumentation amplifier, then filtered by a low pass filter (cutoff frequency about 1 Hz). The gain was determined from the Ohmic Instruments Co. manufacturer's specifications and was precisely set (G = 488) to provide a voltage reading (X10) that is approximately equivalent to AH from 5 through 20 g/m^3 at 25°C. Calibration is accomplished by a single offset adjustment to match AH with the anticipated voltage output. The initial calibration used a psychrometric reference (Psychron, Model No. 566, Baltimore, Md.) in ambient air adjusted to a single reference point. The voltage output is a representation of the AH scaled by a factor of 10, and was displayed via a LCD display at the sensor/signal conditioner location.
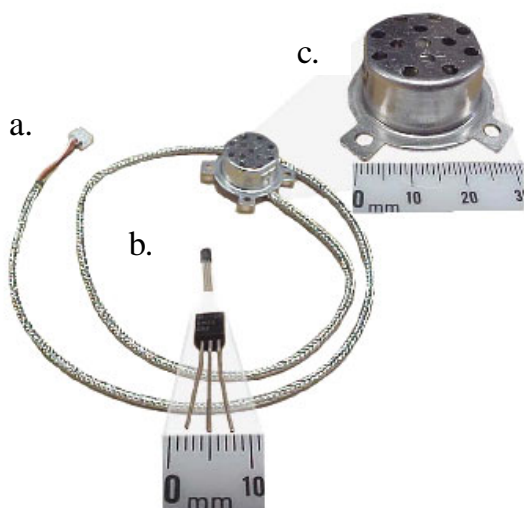

Figure 1. Sensors used in the temperature humidity sensing system (a). A National LM35CA Precision Centigrade Temperature Sensor (b) was used as the temperature sensor and humidity was measured using an absolute humidity sensor (ABS–300) (c) made by Ohmic Instruments Co.

CORRECTIONS

Since the voltage output is only an approximation of the AH, corrected AH values can be obtained from tables supplied by Ohmic Instruments Co. or by correction algorithms. Correction equations were developed from the manufacturer's data specifications and from calibration data. First, all six units were calibrated per manufacturer's recommendations of a single point calibration using a saturated aqueous solution of NaCl (75.3% RH at 25.0°C). The units were then checked at a second point using a saturated solution of LiCl (11.3% RH at 25.0°C). The temperature dependency was established from five temperatures: 10, 20, 25, 30, and 40°C. Statistical software (SAS, 1986) was used to establish the coefficients for a relationship of the form:

$$AH = a*temp + b*temp^2 + c* voltage$$
$$+ d*voltage^2 + intercept \qquad (2)$$

where
    a, b, c, and d are coefficients
    temp = temperature of sensor environment
    voltage = output voltage from AH system

TEMPERATURE SENSOR

The temperature sensor used in the environmental sensor system was a National LM35CA Precision Centigrade Temperature Sensor (fig.1a and 1b, National Data Acquisition Handbook, 1995). The LM35 series provides an output that is linearly proportional to the Celsius temperature. The specifications state that the LM35 does not require any external calibration or trimming to obtain accuracies of ±0.25°C (National Data Acquisition Handbook, 1995). The specifications are for a linear output at +10.0 mV/C, 0.5°C accuracy at 25°C, rated for –55 to +150°C, operates from 4 to 30 V, less than 60 µA current drain, low self–heating, nonlinearity typically only ±0.25°C, long–term stability at ±0.08° C (max) for 1000 hours and low impedance output at 0.1Ω for 1–mA load.

TEMPERATURE MEASUREMENT SYSTEM

The research needs at MARC dictate that a temperature display and a high level output signal be available from the temperature sensing system. A signal conditioner was added to the basic LM35 temperature sensor to achieve offset and scaling capability for fine calibration adjustment. A unity gain low–pass filter (cutoff frequency approx. 1 Hz) was included to remove the majority of electrical noise that was present on the output signal. The voltage output is a direct representation of the temperature scaled by a factor of ten, and was displayed via a LCD display at the sensor/signal conditioner location. Calibration was accomplished using a water bath (PolyScience Digital Temperature Controller, Model 9109, Niles, Ill.).

Six environmental monitoring units (figs. 2a and 2b) for temperature and humidity were constructed for less than $200 including sensors, but without enclosures. Each unit included its own power supply and digital displays for on–site observation of environmental conditions. Temperature sensors were attached to leads of 1–m length and were coated with silicone to provide moisture resistance. The humidity sensor was attached to the monitoring unit and mounted facing downward to minimize dust accumulation. The units
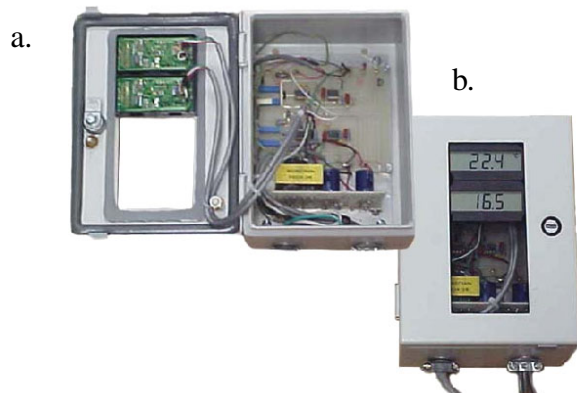
a.

b.

Figure 2. The completed environmental monitoring unit for temperature and humidity showing (a) the circuit board and power supply and (b) the closed cover showing the LCD readout.

were calibrated and put into service as humidity/temperature readout/monitoring units in the USMARC calorimeters and the environmental chambers. The units were used for a period of seven months to provide environmental readings during an experiment designed to study the effect of simulated summer heat waves on cattle.

RESULTS AND DISCUSSION
HUMIDITY

After completion of the cattle experiment all units were removed from service and tested. Absolute humidity measurements were observed to vary between units by about ±1.47 g/m^3 at 12.0 g/m^3, or about $\pm9.3\%$ RH. Some of this variation was considered to be an artifact of the original calibration process. Calibration was revisited using a saturated solution of NaCl and LiCl (Hasegawa, 1985), with known RH values for given temperatures. The procedure dictated putting the sensor in a flask with a saturated salt solution, then the flask was immersed in a constant temperature water bath. Readings were taken when a stable value was achieved. Absolute humidity was determined from a software program called PLUS (Albright, 1990), which factors temperature and barometric pressure into the value. The voltage versus AH correction curve was obtained from the AH system values using SAS (1986). The derived (n = 10,

$R^2 = 0.999$) relationship to correct the AH system output for temperature was:

$$AH = 1.107*voltage^2 + 8.237*voltage -$$
$$0.000483*temp^2 - 0.0407*temp + 0.42844 \qquad (3)$$

This equation was used to convert the voltage outputs to AH for all units.

Corresponding values of relative humidity can be calculated from the derived (n = 10, $R^2 = 0.998$) value for AH as follows:

$$RH = 16.169*AH - 0.669*AH*temp$$
$$+ 0.00780*AH*temp^2 + 0.247 \qquad (4)$$

All six units were calibrated at 25°C with the NaCl solution (75.3% RH) using a single point calibration as recommended by the sensor manufacturer. After approximately one week the sensors were then checked with the NaCl (75.3% RH) and LiCl solution (11.3% RH) at 25°C. The resultant values are shown in table 1. Relative humidity values are shown (table 1) for the saturated solution RH values and the computed RH (eq. 4) from the instrument reading. Offsets were computed for each individual instrument deviation from the saturated solution RH value. The instrument offsets were averaged (six units) and the standard deviation of the offsets computed and reported in table 1. The average RH offsets were 1.35 and –1.20% RH at 75.3 and 11.3% RH, respectively. Corresponding AH values are shown (table 1) for the saturated solution AH values as calculated using the PLUS program (Albright, 1990), which corrects AH for temperature and barometric pressure. Absolute humidity values were computed (eq. 3) from instrument readings. Offsets between the saturated solution values and the instrument readings were computed for individual instruments. The instrument offsets were averaged (six units) and the standard deviation of the offsets computed (table 1). Average AH offsets were –0.038 g/m^3 at 17.6 g/m^3 and 0.342 g/m^3 at 2.6 g/m^3. Unit 6 indicated a 7.2% RH reading for the saturated solution of 11.3%; this sensor provided a consistent low reading for the LiCl measurement, apparently due to an out of tolerance sensor.

TEMPERATURE

At the end of the cattle experiment (seven months) the sensors were checked in the water bath (5.0, 20.0, and

Table 1. Saturated solutions of NaCL and LiCL provided humidity standards for comparison of units. Relative and absolute humidity readings shown for each instrument along with average offsets and standard deviation of the offsets.

Unit	1	2	3	4	5	6	Average Offset and Std. Dev.[b]
Relative Humidity (actual/measured)[a]							
NaCl	75.3/76.1	75.3/76.5	75.3/76.3	75.3/76.0	75.3/78.5	75.3/76.5	1.35±0.93%
LiCl	11.3/10.1	11.3/11.4	11.3/10.9	11.3/10.0	11.3/11.0	11.3/7.2	–1.20±1.52%
Absolute Humidity (actual/measured) [c]							
NaCl	17.62/17.56	17.62/17.64	17.64/17.61	17.64/17.53	17.67/18.11	17.67/17.64	–0.038±0.201 g/m^3
LiCl	2.62/2.28	2.62/2.57	2.62/2.47	2.62/2.25	2.62/2.50	2.62/1.60	0.342±0.36 g/m^3

[a] Relative humidity values based on a saturated solution (NaCl 75.3% at 25.0°C and LiCl at 25.0°C). Offsets were computed for each individual instrument deviation from the saturated solution RH value. The instrument offsets were averaged (six units) and the standard deviation of the offsets computed.

[b] The instrument offsets were averaged (six units) and the standard deviation of the offsets computed.

[c] Absolute humidity values were calculated for the saturated solution values using the PLUS program (Albright, 1990) that corrects AH for temperature and barometric pressure. Absolute humidity values were computed (eq. 3) from instrument readings. Offsets between the saturated solution values and the instrument readings were computed for individual instruments.

Table 2. Temperature sensor readings at the end of seven months.

Set Temp. (°C)[a]	Unit						Average Offset±Std. Dev.[b]
	1	2	3	4	5	6	
5.0	5.50	5.46	5.35	5.35	4.99	5.64	0.39±0.22°C
20.0	20.22	20.22	20.14	20.18	19.81	20.33	0.15±0.18°C
35.0	35.10	35.08	35.07	34.97	35.03	34.99	0.04±0.05°C

[a] Single measurements taken when water bath (PolyScience Digital Temperature Controller, Model 9109) readings stabilized.

[b] The average of offset from setpoint and standard deviation is over the six individual units.

35.0°C) with values recorded upon reaching stable readings. The group had the values shown in table 2. The average deviations from the calibrated values were 0.39, 0.15, and 0.04°C at 5, 20, and 35°C, respectively. All units fell within the LM34 specifications of ±0.5°C at 25°C.

CONCLUSIONS

An environmental monitoring system was developed and tested that allowed temperature and humidities to be monitored in harsh environments. Six temperature and humidity measurement systems were constructed to provide continuous monitoring of environmental chamber thermal conditions. After seven months in use, the temperature units provided accuracies within the manufacturer's specifications for the temperature sensor devices (±0.5°C accuracy at 25°C). The AH measurement systems were calibrated using a saturated salt solution. Short–term (one week) stability tests indicate the units have good accuracy (offset of –0.038 g/m^3 at 17.6 g/m^3 and 0.342 g/m^3 at 2.6 g/m^3). The overall performance of the temperature and humidity system was acceptable for thermal environment monitoring applications. The demonstrated reliability may justify the additional complexity of construction and calibration for certain applications that involve harsh environments.

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